Sweet Spot Supersymmetry and LHC

Masahiro Ibe (SLAC)

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Based on works with
Ryuichiro Kitano (LANL)

hep-ph/0611111
0705.3686 [hep-ph]
0710.3796 [hep-ph]
0712.3300 [hep-ph]

Introduction

- LHC is coming soon.

The MSSM is one of the most motivated candidates for the beyond the SM.

To list “well-motivated” models with simple parameterization is still important.

If the model predicts distinctive features, so much the better.

Introduction

Sweet Spot Supersymmetry

Gauge Mediation Model for Gaugino + Matter

+

Direct couplings between Higgs and Hidden Sectors

(μ-term + Higgs soft masses)

- No μ-problem, No SUSY CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- Consistent gravitino DM scenario

Table of contents

Part I

How it’s made and How it works.

SUSY Breaking & Mediation Mechanisms

- Let us assume that the SUSY is mainly broken by an F-term of $S = (s, \psi_S, F_S)$.

scalar

Goldstino

F-term

(non vanishing)

SUSY Breaking & Mediation Mechanisms

- Let us assume that the SUSY is mainly broken by an F-term of $S = (s, \psi_S, F_S)$.

- In terms of S , we can write down an effective theory of SUSY breaking sector;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \cdots$$

$$W = m^2 S$$

Higher oder terms

Tadpole term for SUSY breaking

Λ is the mass scale of the massive fields.

SUSY Breaking & Mediation Mechanisms

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \cdots$$
$$W = m^2 S$$

- F-term $\langle F_S \rangle = m^2$
- Scalar mass $m_S = 2\frac{\langle F_S \rangle}{\Lambda}$
- Gravitino (Goldstino) $m_{3/2} = \frac{\langle F_S \rangle}{\sqrt{3}M_P}$

We can discuss physics of hidden sector below the scale Λ, with this effective theory with only two parameters $(m_{3/2}, \Lambda)$.

SUSY Breaking & Mediation Mechanisms

- The origin of Gaugino masses are classified by how S couples to gauge supermultiplets

$$W \ni f(S)\mathcal{W}^\alpha \mathcal{W}_\alpha$$

- Gravity Mediation

$$f(S) \simeq \frac{S}{M_P} \longrightarrow m_{\text{gaugino}} \simeq \frac{\langle F_S \rangle}{M_P} = O(m_{3/2})$$

This choice of $f(S)$ suggests that S cannot carry any charge. $\longrightarrow$ Polonyi/Gravitino Problem

Gravity mediation scenario also suffers from FCNC problem and CP problem.

SUSY Breaking & Mediation Mechanisms

- The origin of Gaugino masses are classified by how S couples to gauge supermultiplets

$$W \ni f(S)\mathcal{W}^\alpha \mathcal{W}_\alpha$$

- Gauge Mediation
  (after integrating out the messenger particles)

$$f(S) = \frac{g^2 N_{\text{mess}}}{(4\pi)^2} \log S$$

$$\longrightarrow \quad m_{\text{gaugino}} \simeq \frac{g^2}{(4\pi)^2} \frac{\langle F_S \rangle}{\langle s \rangle} = \frac{g^2}{(4\pi)^2} \frac{M_P}{\langle s \rangle} O(m_{3/2})$$

S can be charged field $\longrightarrow$ No Polonyi Problem

Gauge mediation scenario also solves FCNC problem.

SUSY Breaking & Mediation Mechanisms

- What's wrong with Gauge Mediated Model?

$\mu/B\mu$ -Problem

Supersymmetric Higgs mixing term

$$W \ni \mu H_u H_d$$

SUSY breaking Higgs mixing term

$$\mathcal{L} \ni B\mu H_u H_d$$

From naturalness of EWSB, both two parameters are required to be comparable to or less than the weak scale.

SUSY Breaking & Mediation Mechanisms

- What's wrong with Gauge Mediated Model?

$\mu/B\mu$ -Problem

- Why $\mu = O(m_{\text{gaugino}})$?

- Many attempts end up with too large B-term.

ex)

$$K \ni \frac{1}{(4\pi)^2}\frac{S^\dagger}{S}H_u H_d$$

$$\mu = \frac{1}{(4\pi)^2}\frac{\langle F_S\rangle}{\langle s\rangle} = O(m_{\text{gaugino}})$$

$$\frac{B\mu}{\mu} = \frac{\langle F_S\rangle}{\langle S\rangle} = (4\pi)^2 O(m_{\text{gaugino}})$$

Sweet Spot Supersymmetry

Gauge Mediated ~~SUSY~~ masses to Gaugino + Matter

+

Direct couplings between Higgs and Hidden Sectors

(μ-term + Higgs soft masses)

- No μ-problem, No CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- New production mechanism of gravitino DM

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$$+ \left(1 - \frac{4g^4}{(4\pi)^4} C_2 (\log |S|)^2 \right) \Phi^\dagger \Phi$$

$$W = W_{\text{Yukawa}} + m^2 S + w_0$$

$$+ \frac{1}{2} \left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right) \mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

Sweet Spot Supersymmetry

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SUSY breaking sector

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

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$$+ \frac{1}{2} \left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right)$$

R-symmetry is broken by the cosmological constant!

$$\langle S \rangle = \boxed{\frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P}} + \boxed{\langle F_S \rangle \theta^2}$$

$$V(s) \simeq m_S^2 |s|^2 \underline{-2m^2 |w_0| s}$$

supergravity

$$m_S^2 = 4 \frac{m^4}{\Lambda^2}$$

$$|w_0| \simeq m^2 M_{\text{Pl}} / \sqrt{3},$$

$$(\langle V \rangle \simeq |m^2|^2 - 3|w_0|^2 \simeq 0)$$

$$\boxed{\langle s \rangle \simeq 2 \frac{m^2 |w^0|}{m_S^2} \neq 0}$$

['06 R.Kitano]

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

$$K = \boxed{S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}} \longleftarrow \text{SUSY breaking sector}$$

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right)$$

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R-symmetry is broken by the cosmological constant!

$$\langle S \rangle = \boxed{\frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P}} + \boxed{\langle F_S \rangle \theta^2}$$

$$V(s) \simeq m_S^2 |s|^2 \underbrace{-2 m^2 |w_0| s}_{\text{supergravity}}$$

$$m_S^2 = 4 \frac{m^4}{\Lambda^2}$$

$$|w_0| \simeq m^2 M_{\text{Pl}} / \sqrt{3},$$

$$(\langle V \rangle \simeq |m^2|^2 - 3 |w_0|^2 \simeq 0)$$

$$\boxed{\langle s \rangle \simeq \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P}}$$

['06 R.Kitano]

Supersymmetry

SS is given by;

Messenger particle (5,5*)

$$W = kS\Psi\bar{\Psi}$$

Messenger Mass

$$M_{\text{mess}} = k\langle s\rangle$$

mass splitting of messenger bosons

$$\begin{pmatrix} k^2|\langle s\rangle|^2 & kF \\ kF^* & k^2|\langle s\rangle|^2 \end{pmatrix} \longrightarrow |k\langle s\rangle|^2 \pm |kF|$$

Gauge Mediated SUSY Breaking

$$- \frac{c_H S^\dagger S(H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$$+ \left(1 \boxed{- \frac{4g^4}{(4\pi)^4} C_2 (\log|S|)^2}\right) \Phi^\dagger \Phi$$

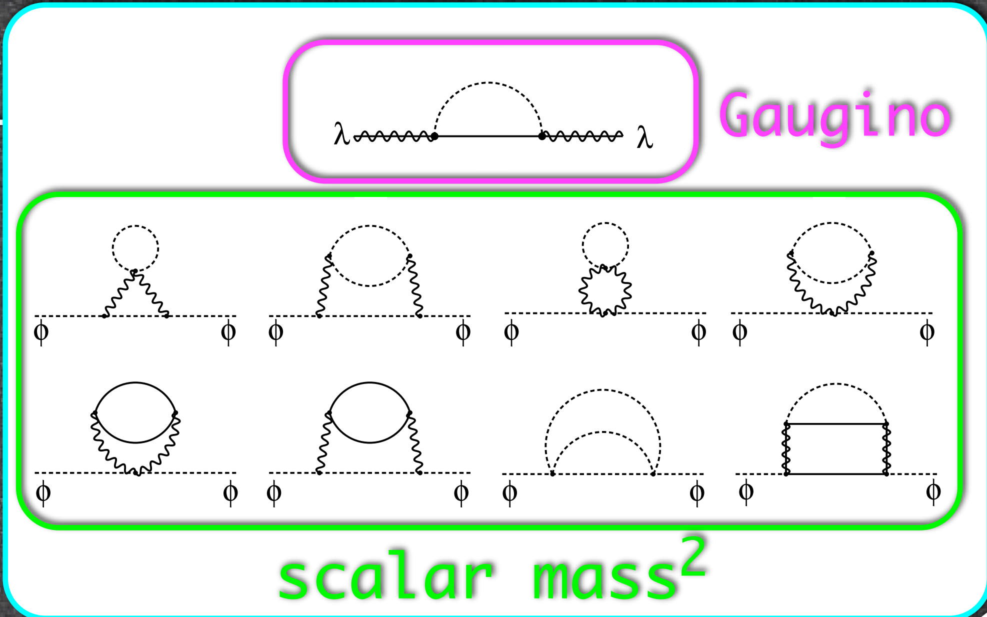
$$W = W_{\text{Yukawa}} + m^2 S + w_0$$

$$+ \frac{1}{2}\left(\frac{1}{g^2} \boxed{- \frac{2}{(4\pi)^2} \log S}\right) \mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\langle S\rangle = \frac{\sqrt{3}}{6}\frac{\Lambda^2}{M_P} + \langle F_S\rangle\theta^2$$

Supersymmetry

SS is given by;



Gauge Mediated SUSY Breaking

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Sweet Spot Supersymmetry

In terms of S, SSS is given by;

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$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

Gauge Mediated SUSY Breaking

$$m_{\mathrm{gaugino}} = \frac{g^2}{(4\pi)^2} \frac{\langle F_S \rangle}{\langle s \rangle}$$

$$m^2_{\mathrm{scalar}} = \left(\frac{g^2}{(4\pi)^2} \right)^2 \cdot 2C_2 \left| \frac{\langle F_S \rangle}{\langle s \rangle} \right|^2$$

$$\frac{\langle F_S \rangle}{\langle s \rangle} = \frac{2\sqrt{3} m^2 M_P}{\Lambda^2} = 6 m_{3/2} \left(\frac{M_P}{\Lambda} \right)^2$$

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

direct coupling between SUSY breaking and Higgs sector (Giudice-Masiero Mechanism)

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda}{M_P} + \langle F_S \rangle \theta^2$$

Approximate U(1)-symmetry

$S : +2 \quad H_u : +1 \quad H_d : +1$

$$\mu = c_\mu \frac{\langle F_S \rangle}{\Lambda} \sim m_{3/2} \left(\frac{M_P}{\Lambda} \right)$$

$$B = O(m_{3/2})$$

$\longrightarrow$ small CP-phase

$$m_{H_{u,d}}^2 = c_H \left| \frac{\langle F_S \rangle}{\Lambda} \right|^2$$

$$\sim m_{3/2}^2 \left(\frac{M_P}{\Lambda} \right)^2$$

Sweet Spot Supersymmetry

Gauge Mediated masses

$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

Giudice-Masiero mechanism + U(1)-symmetry

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)$$

$B = O(m_{3/2}) \longrightarrow$ No CP-problem

Sweet Spot $\quad (c_\mu = O(1))$

$$m_{\text{gaugino}} \sim \mu \rightarrow \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \rightarrow \boxed{\Lambda \sim M_{\text{GUT}}}$$

$$m_{\text{gaugino}} = O(100)\,\text{GeV} \longrightarrow \boxed{m_{3/2} = O(1)\,\text{GeV}}$$

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \left(\frac{c_\mu S H_u H_d}{\Lambda} + \text{h.c.}\right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2} + \left(1 - \frac{4g^4}{(4\pi)^4} C_2 (\log|S|)^2\right) \Phi^\dagger \Phi$$

$$W = W_{\text{Yukawa}} + m^2 S + w_0 + \frac{1}{2}\left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S\right) \mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

$$\rightarrow \boxed{\langle s \rangle \simeq 10^{14}\,\text{GeV} \qquad \sqrt{F_S} \simeq 10^9\,\text{GeV}}$$

These are supported by gravitino DM produced by the decay of “s”.

Free Parameters

$$\Lambda \qquad c_\mu \qquad c_H \qquad m^2 \qquad M_{\text{mess}}$$

Sweet Spot Supersymmetry

Gauge Mediated masses

$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

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These are supported by gravitino DM produced by the decay of "s".

Free Parameters

$$m_{\tilde g} \quad \mu \quad m^2_{H_{u,d}} \quad m_{3/2} \quad M_{\text{mess}}$$

Sweet Spot Supersymmetry

Gauge Mediated masses

$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

Giudice-Masiero mechanism + U(1)-symmetry

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Sweet Spot $\quad (c_\mu = O(1))$

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$$\boxed{\begin{array}{l} \langle s \rangle \simeq 10^{14}\,\text{GeV} \\ \sqrt{F_S} \simeq 10^{9}\,\text{GeV} \end{array}}$$

These are supported by gravitino DM produced by the decay of “s”.

Free Parameters (EWSB)

$$m_{\tilde{g}} \qquad \mu \qquad \cancel{m^2_{H_{u,d}}} \qquad m_{3/2} \qquad M_{\text{mess}}$$

Sweet Spot Supersymmetry

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \left(\frac{c_\mu S H_u H_d}{\Lambda} + \text{h.c.}\right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2} + \left(1 - \frac{4g^4}{(4\pi)^4} C_2 (\log |S|)^2\right) \Phi^\dagger \Phi$$

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Gauge Mediated masses

$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

Giudice-Masiero mechanism + U(1)-symmetry

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)$$

$B = O(m_{3/2}) \longrightarrow$ No CP-problem

Sweet Spot $(c_\mu = O(1))$

$$m_{\text{gaugino}} \sim \mu \longrightarrow \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \longrightarrow \boxed{\Lambda \sim M_{\text{GUT}}}$$

$$m_{\text{gaugino}} = O(100)\,\text{GeV} \longrightarrow \boxed{m_{3/2} = O(1)\,\text{GeV}}$$

Low energy phenomenology

Cosmology

Free Parameters (EWSB)

$$m_{\tilde{g}} \quad \mu \quad \cancel{m^2_{H_{u,d}}} \quad m_{3/2} \longleftarrow M_{\text{mess}}$$

How sweet is the sweet spot?

Gauge Mediated masses

$$m_{\rm gaugino} \simeq m_{\rm scalar} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

Giudice-Masiero mechanism + PQ-symmetry

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)$$

gravitino Dark Matter

$$\Omega_{3/2} h^2 = 0.1 \times \left(\frac{m_{3/2}}{500 \text{ MeV}}\right)^{3/2} \left(\frac{\Lambda}{1 \times 10^{16} \text{ GeV}}\right)^{3/2}$$

provided by the decay of the coherent oscillation of the scalar "s".

How sweet is the sweet spot?

Gauge Mediated masses

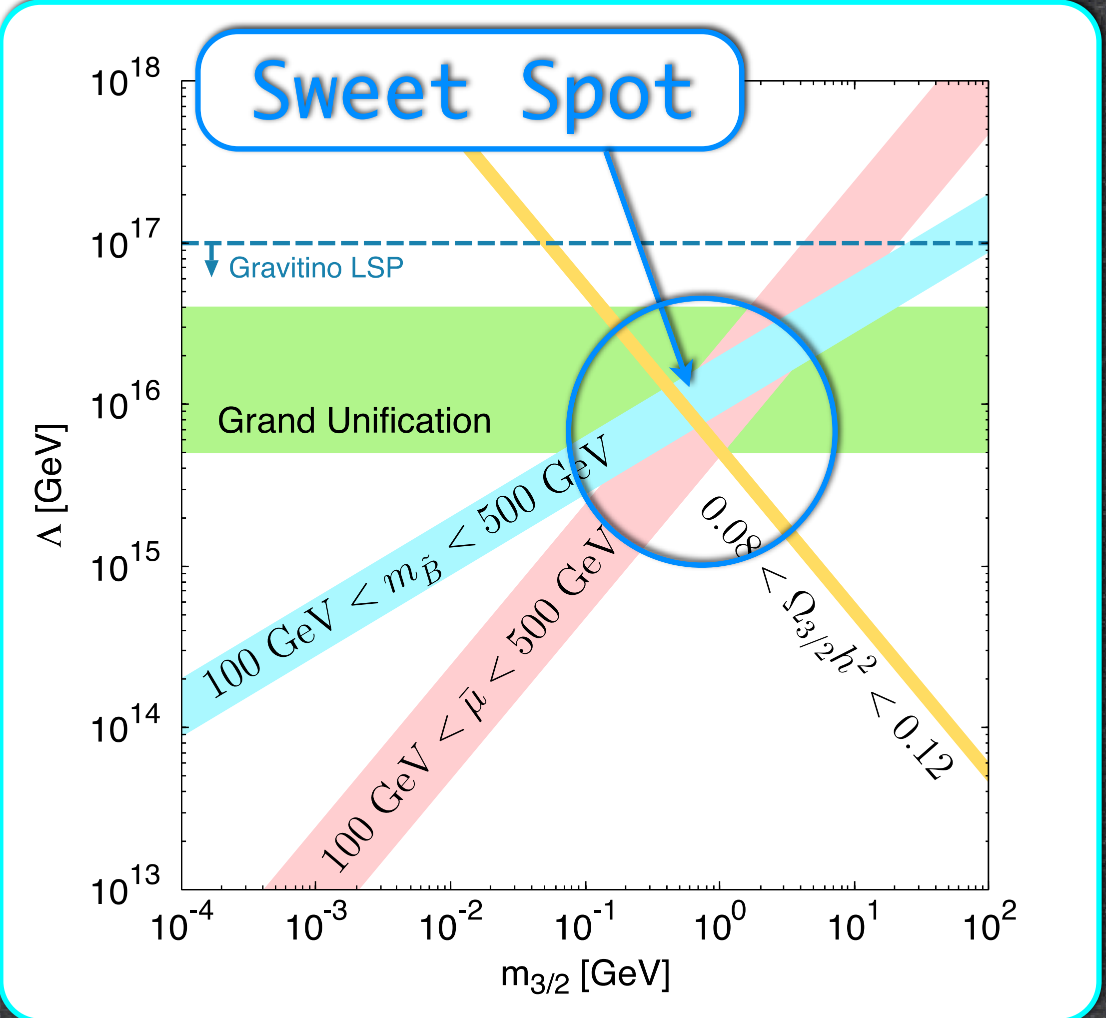
$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/}$$

Giudice-Masiero mechanism

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda} \right)$$

gravitino Dark Matter

$$\Omega_{3/2} h^2 = 0.1 \times \left(\frac{m_{3/2}}{500 \text{ MeV}} \right)^{3/2} \Bigg($$



Summary of the model building

- U(1) symmetric Giudice Masiero terms

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

- Small breaking of the U(1) symmetry

$$W = m^2 S + m_{3/2} M_P^2 \longrightarrow \cancel{\text{SUSY}} \; \& \; \cancel{\text{R}}$$

- Gauge Mediation via $W = kS\bar{\psi}\psi$

Sweet Spot

$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda} \right)^2$$

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda} \right)$$

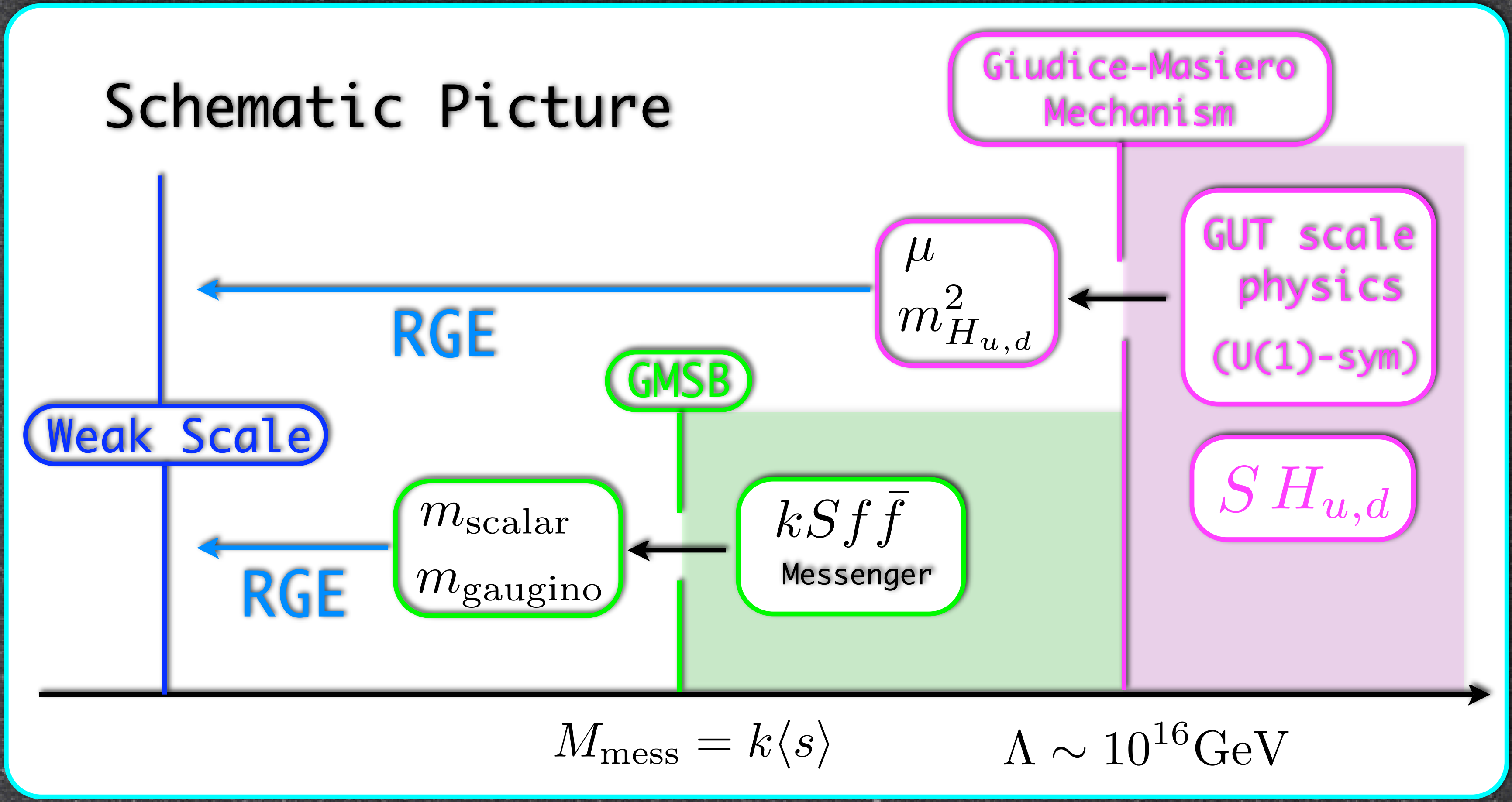
$\longrightarrow$

$$\boxed{\begin{array}{l} \Lambda \sim M_{\text{GUT}} \\ m_{3/2} = O(1)\,\text{GeV} \end{array}}$$

Part II

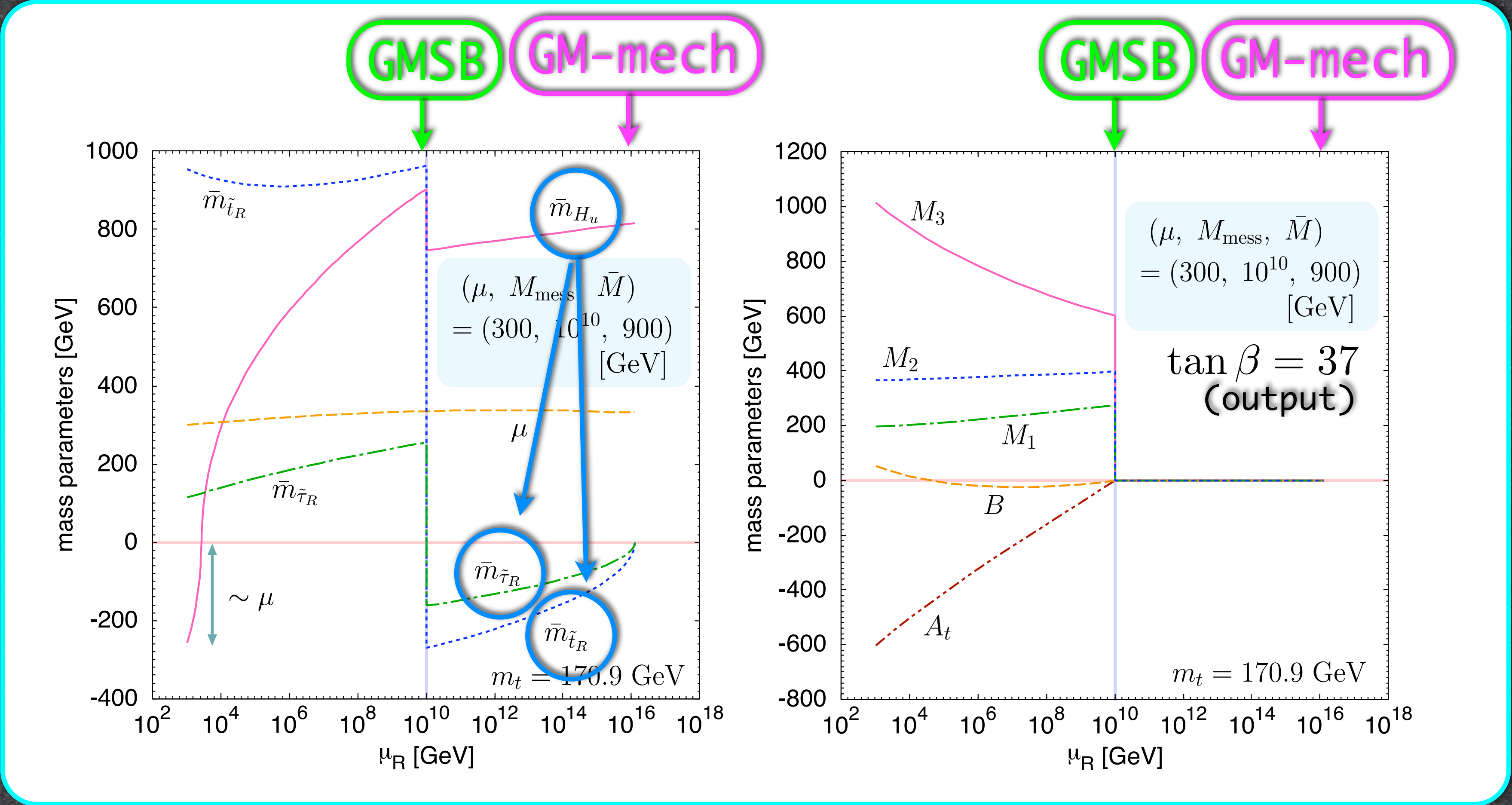
Phenomenology

Typical Mass Spectrum



Two mediation scale $\longrightarrow$ Peculiar spectrum

Typical Mass Spectrum



$m^2_{H_{u,d}}$ affect other scalar masses between Λ and $M_{\rm mess}$

$\longrightarrow$ SSS predicts light stau $(m^2_{H_{d,u}} > 0)$

Typical Mass Spectrum

An example of UV-model

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.}\right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$\uparrow$ (One-loop calculation)

$$W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} XY \ ,$$ O'Raifeartaigh Model

$$W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q X + M_q q \bar{q} \ ,$$ (U(1)-sym)

These superpotentials can be embedded into a product group GUT model (SO(9)XSU(5) or SO(6)XSU(5)) ['06 R. Kitano].

$$\longrightarrow M_{XY} \sim M_q \sim M_{\text{GUT}} \simeq 10^{16} \text{GeV}$$

Typical Mass Spectrum

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('84 Dine,Fischler,Nemeschansky)

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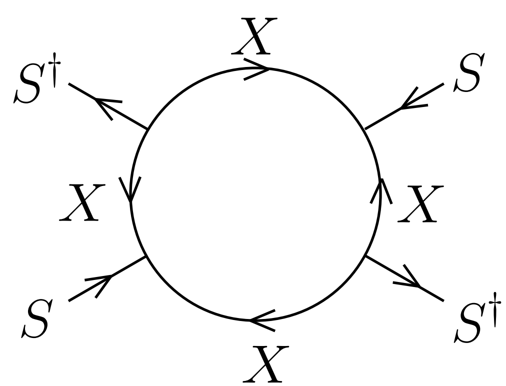
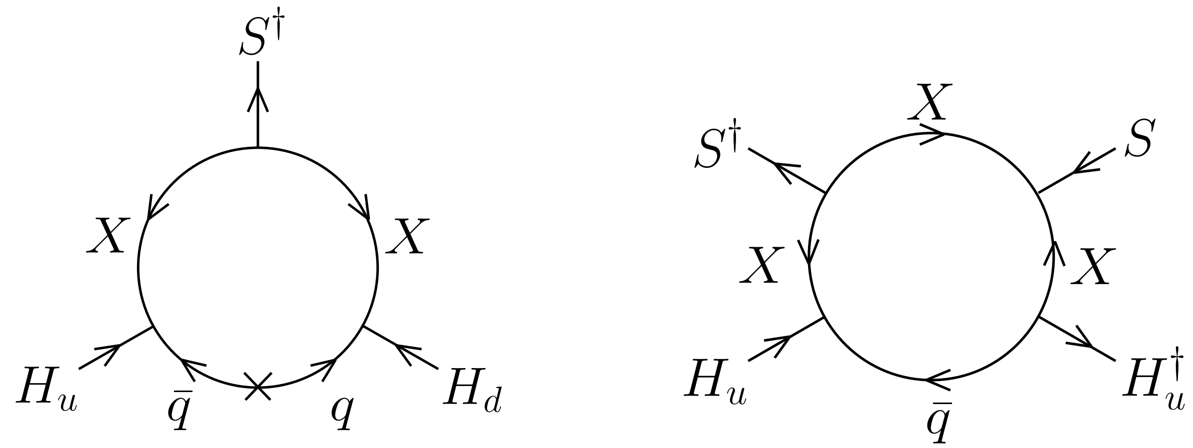


Typical Mass Spectrum

An example of UV-model

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \boxed{\left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.}\right)} - \boxed{\frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}}$$



$$W_{\rm Higgs} = h H_u \bar{q} X + \bar{h} H_d q X + M_q q \bar{q} \ ,$$

Typical Mass Spectrum

An example of UV-model

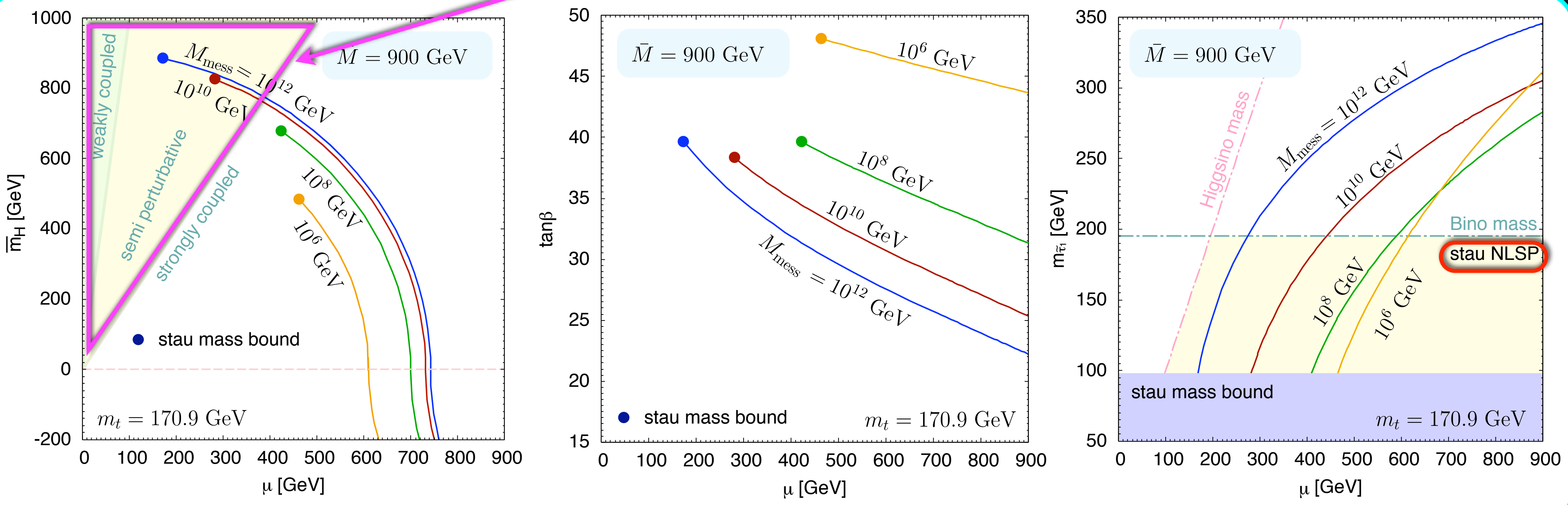
$$\boxed{K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \mathrm{h.c.}\right) - \frac{c_H S^\dagger S(H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}}$$

Perturbative example

$$\left\{\begin{array}{l} m_{H_{u,d}}^2 > 0 \xrightarrow{\text{(RGE)}} \text{Light Stau} \\ m_{H_{u,d}}^2 \sim \text{(1-loop)}, \ \mu \sim \text{(1-loop)} \\ \longrightarrow \ \mu/m_{H_{u,d}} \sim \text{(1-loop)}^{1/2} \end{array}\right.$$

Typical Mass Spectrum

Prediction of (simple perturbative) SSS



Light Stau (Stau NLSP can be easily realized)

Light Higgsino

Large tanβ

Sweet Spot Supersymmetry

Three low energy parameters $(\mu, M_{\mathrm{mess}}, \bar{M})$

$$m_{\mathrm{gaugino}} = g^2 \bar{M}$$

We can reconstruct model parameters by measuring three masses.

LHC Signatures

Benchmark Point

$$\mu = 300 \text{ GeV} \ , \quad M_{\text{mess}} = 10^{10} \text{ GeV} \ , \quad \bar{M} = 900 \text{ GeV}.$$

→ Stau NLSP(116GeV)
(lifetime O(10000)sec.)

→ $\chi_1^0 \quad \chi_2^0 \quad \chi_3^0 \quad \chi_4^0$

Bino Higgsino Wino

→ gluinos, squarks ~ 1TeV

$$\sigma(pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}) \simeq 1.4\,\text{pb}$$

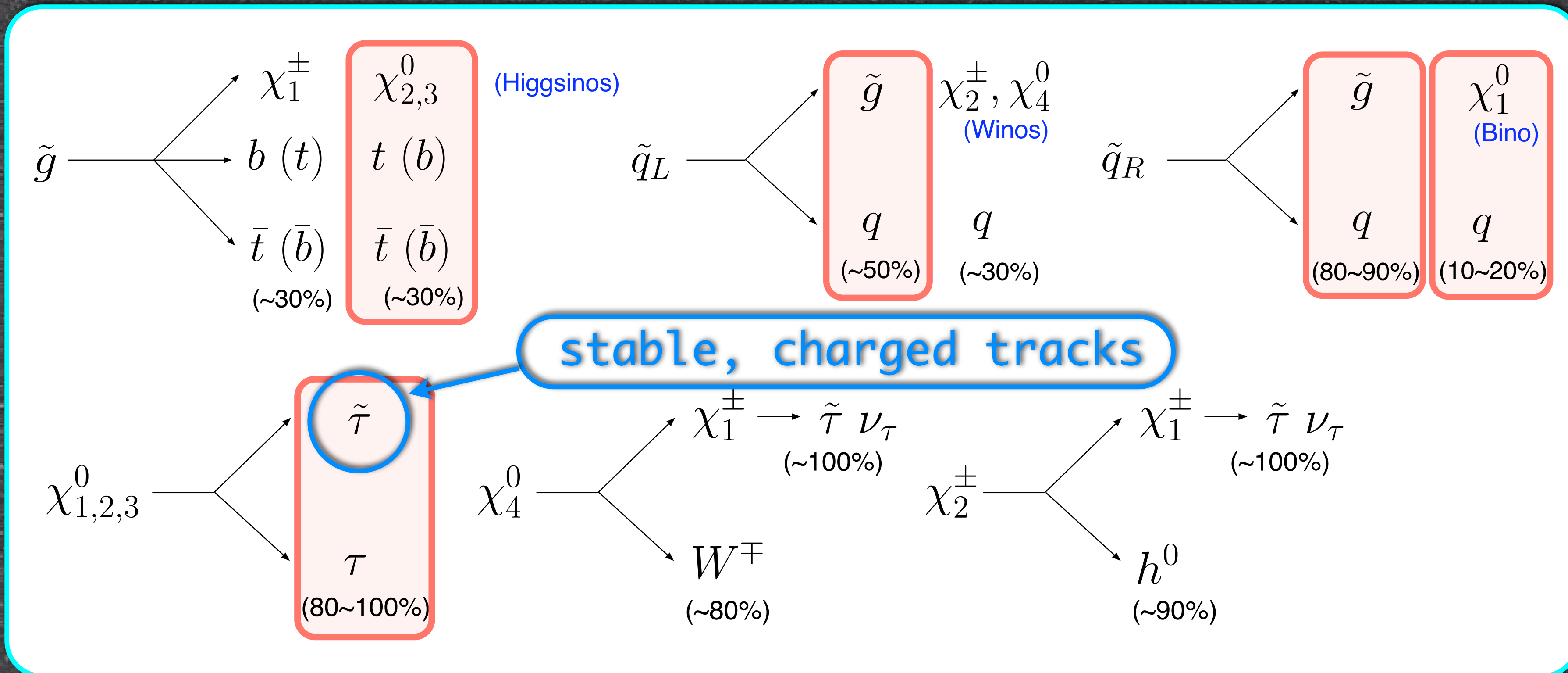
Spectrum

$\tilde{g}$	1013	$\tilde{\nu}_L$	543
$\chi_1^{\pm}$	270	$\tilde{t}_1$	955
$\chi_2^{\pm}$	404	$\tilde{t}_2$	1177
χ_1^0	187	$\tilde{b}_1$	1128
χ_2^0	276	$\tilde{b}_2$	1170
χ_3^0	307	$\tilde{\tau}_1$	116
χ_4^0	404	$\tilde{\tau}_2$	510
$\tilde{u}_L$	1352	$\tilde{\nu}_\tau$	502
$\tilde{u}_R$	1263	h^0	115
$\tilde{d}_L$	1354	H^0	770
$\tilde{d}_R$	1251	A^0	765
$\tilde{e}_L$	549	$H^{\pm}$	775
$\tilde{e}_R$	317	$\tilde{G}$	0.5

$\tan\beta = 37$
(output)

LHC Signatures

Decay modes



Typical Event at LHC

Many b/τ-jets + low-velocity 2 charged tracks

LHC Signatures

Stau Mass Measurement

$$m_{\tilde{\tau}_1} = \frac{p_{\tilde{\tau}_1}}{\beta\gamma}$$

measured from charged track

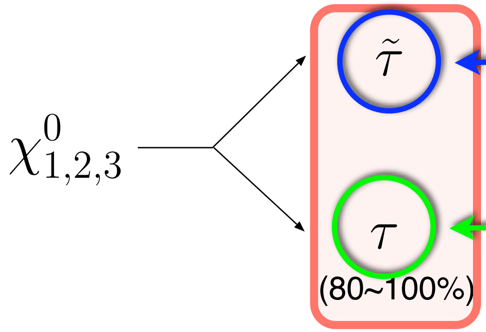
time of flight measurement

['00 Ambrosanio,Mele,Petrarca,Polesello,Rimoldi]

For $m_{\tilde{\tau}_1} \simeq$ 100GeV stau mass can be measured with an accuracy of 100MeV.

LHC Signatures

Reconstruction of neutralino masses



charged track

We use hadronic decay mode of τ
['98 Hinchiliffe & Paige]

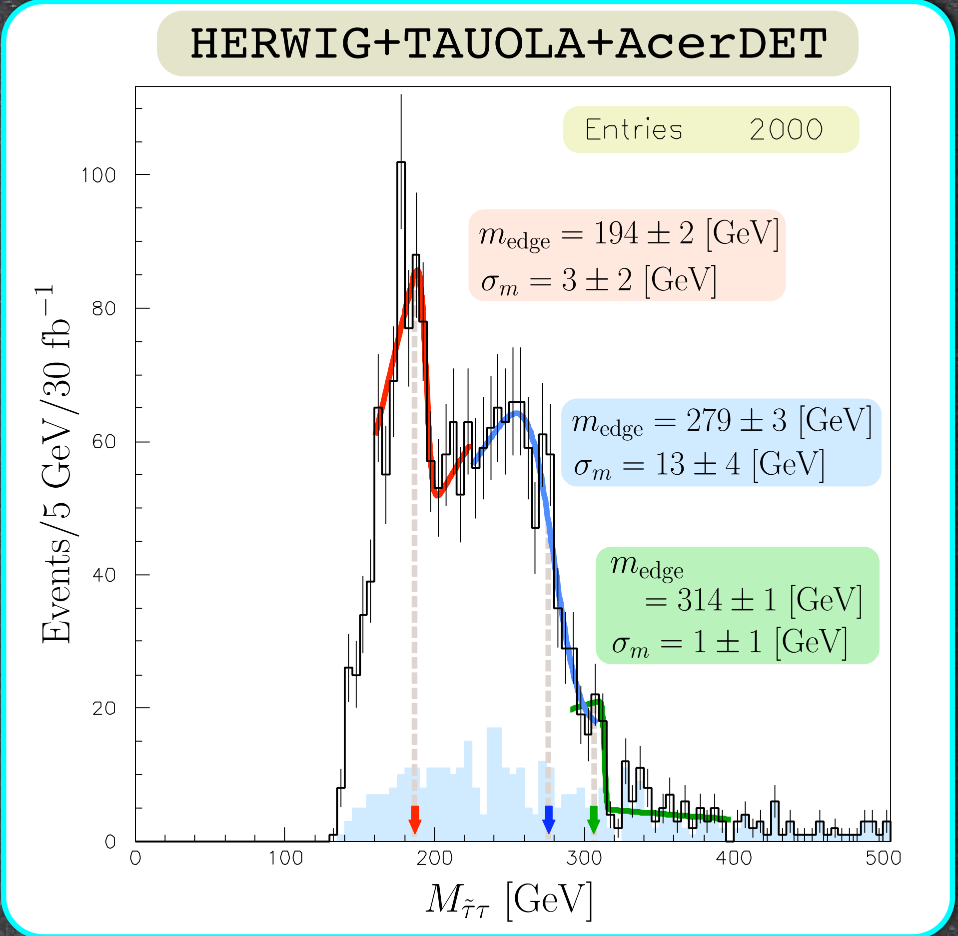
cf.The analysis with leptonic modes discussed in ['06 Ellis,Raklev,Oye] is difficult in our case.

Select events with 2 stau candidates.
(one of them should be slow $\beta\gamma < 2.2$)

Select events with 1 tau-jet candidate.

(within the triggered events with the condition in ATLAS TDL)

LHC Signatures



42,900 (30fb^{-1}) SUSY event

After triggering and selection

2000 event candidates

Main background

Wrong combination of tau-stau

We chose a stau for the smaller invariant mass. (efficiency 70%)

Miss-tagging of non-tau-jet

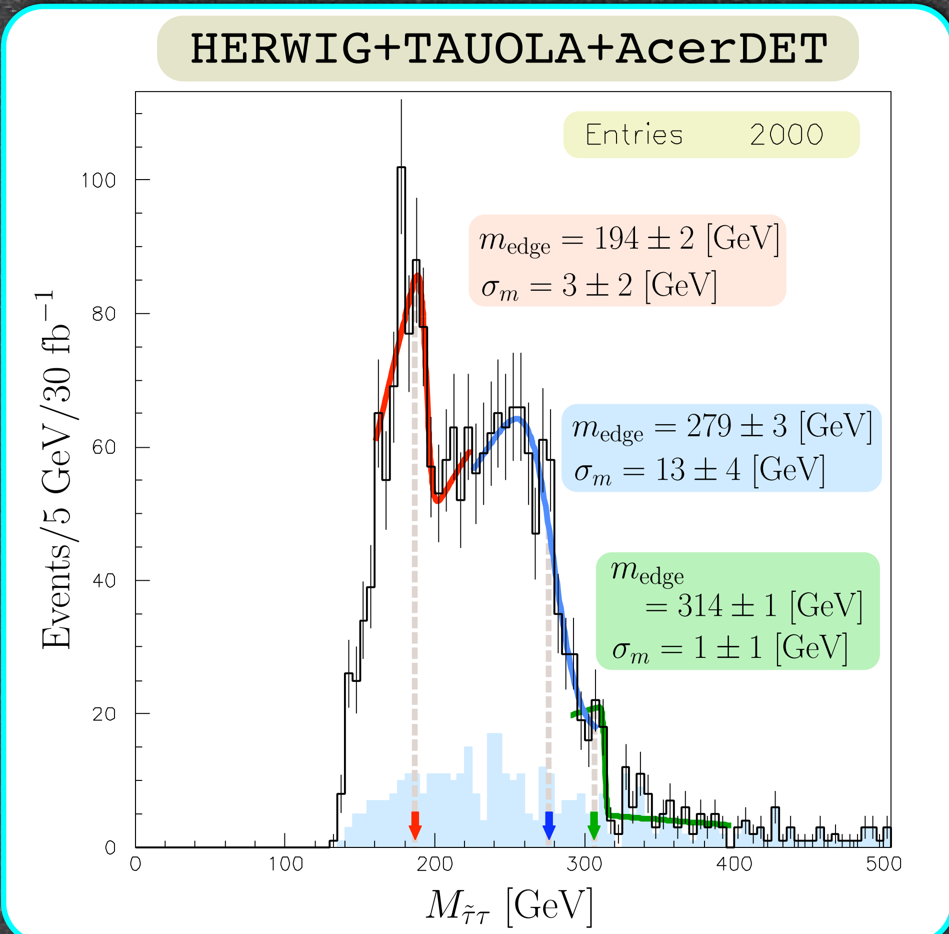
tau-tag efficiency 50%

mis-tag probability 1%

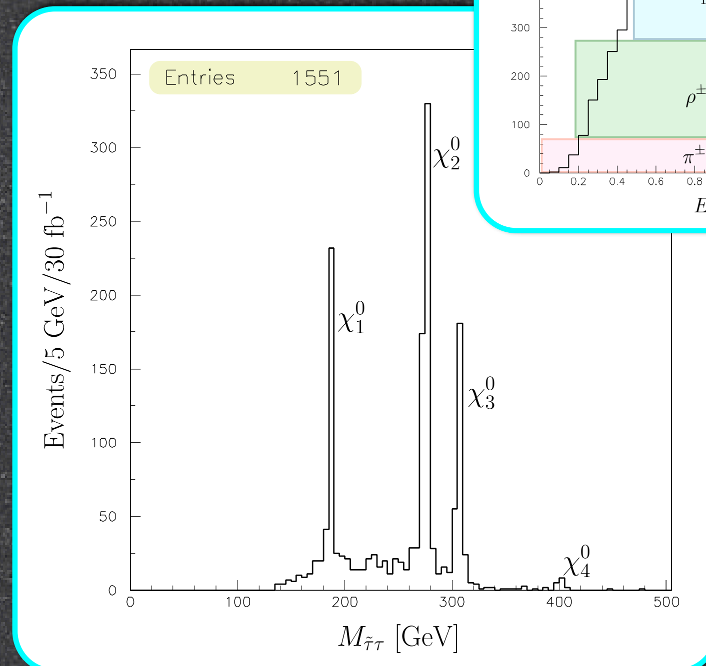
(437 events are mis-tagged events)

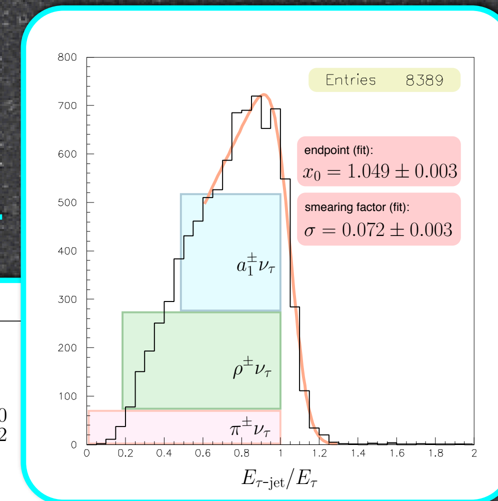
We can determine masses of χ_1^0, χ_2^0 with an accuracy of O(5)%.

LHC Signatures



Neutrinos carry away part of energy.





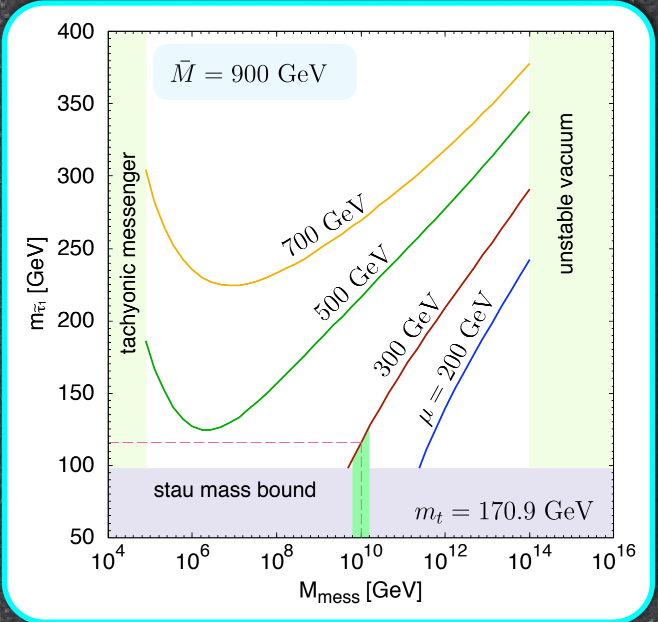
We can determine masses of χ_1^0, χ_2^0 with an accuracy of O(5)%.

LHC Signatures

Parameter Reconstruction

$$\boxed{m_{\chi^0_{1,2}} \longrightarrow \mu,\ \bar{M}}$$

$$\boxed{m_{\tilde{\tau}_1} \longrightarrow M_{\text{mess}}}$$

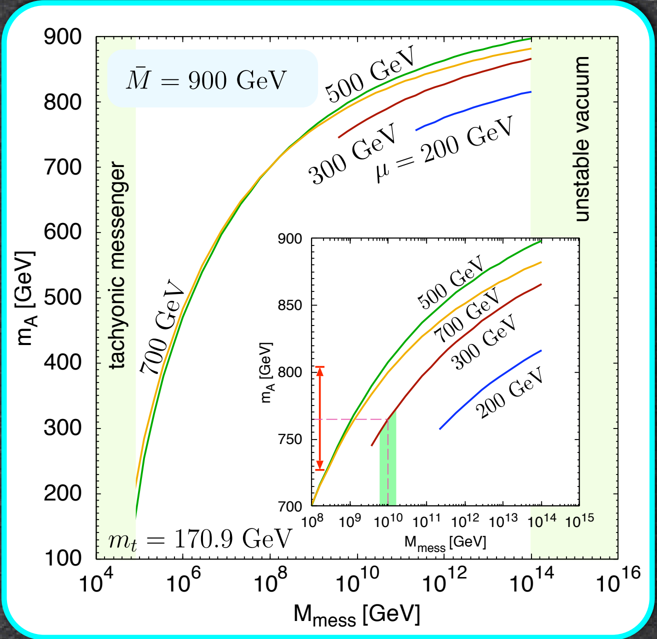


$$\boxed{\Delta\mu \sim 20\,\text{GeV} \quad \Delta\bar{M} \sim 50\,\text{GeV} \quad \Delta\log_{10} M_{\text{mess}} \sim 0.2}$$

Consistency Check

Prediction of M_A

$$\boxed{M_A = 745 \pm 40\,\text{GeV}}$$



We can perform non-trivial check!

Summary

Sweet Spot Supersymmetry

Gauge Mediation + Giudice-Masiero Mechanism
(+U(1)-symmetry)

- Higgs doublets directly couples with Hidden Sector at the GUT scale!

  No surprise, since Higgs doublets always requires special interactions at the GUT scale!

- The small breaking of the U(1)-symmetry triggers the SUSY breaking!

Summary

Sweet Spot Supersymmetry

Gauge Mediation + Giudice-Masiero Mechanism
(+U(1)-symmetry)

- No μ-problem, No CP-problem
- Light Stau + Light Higgsino
  Collider signals are different from minimal gauge mediation.
- MSSM is determined by three parameters
  We can perform consistency check of the model at LHC.
- (Successful gravitino dark matter)

AcerDET

Isolated Leptons, Photon

Isolated from other clusters by $\Delta R = 0.4$.

Transverse energy deposited in cells in a cone $\Delta R = 0.2$ around the cluster is less than 10GeV.

Jet

A cluster is recognized as a jet by a cone-based algorithm if it has $p_T > 15$ GeV in a cone $\Delta R = 0.4$.

Labeled either as a light jet, b-jet, c-jet or τ-jet, using information of the event generators.

A flavor independent calibration of jet four-momenta optimized to give a proper scale for the di-jet decay of a light Higgs boson.

Smearing of Stau momentum/velocity

resolution of the stau velocity

$$\frac{\sigma(\beta)}{\beta} = 2.8\% \times \beta.$$

sagitta measurement error

$$\frac{\sigma(p_{\tilde{\tau}_1})}{p_{\tilde{\tau}_1}} = 0.0118\% \times (p_{\tilde{\tau}_1}/\mathrm{GeV}),$$

multiple scattering effect

$$\frac{\sigma(p_{\tilde{\tau}_1})}{p_{\tilde{\tau}_1}} = 2\% \times \sqrt{1 + \frac{m_{\tilde{\tau}_1}^2}{p_{\tilde{\tau}_1}^2}},$$

fluctuation of energy loss in the calorimeter

$$\frac{\sigma(p_{\tilde{\tau}_1})}{p_{\tilde{\tau}_1}} = 89\% \times (p_{\tilde{\tau}_1}/\mathrm{GeV})^{-1}$$

Event Selection

Triggering ['99 Atlas Collabolation]

- one isolated electron with $p_T > 20$ GeV;
- one isolated photon with $p_T > 40$ GeV;
- two isolated electrons/photons with $p_T > 15$ GeV;
- one muon with $p_T > 20$ GeV;
- two muons with $p_T > 6$ GeV;
- one isolated electron with $p_T > 15$ GeV
  + one isolated muon with $p_T > 6$ GeV;
- one jet with $p_T > 180$ GeV;
- three jets with $p_T > 75$ GeV;
- four jets with $p_T > 55$ GeV.

Isolated electrons/photons, muons and jets in the central regions of pseudorapidity $|\eta| < 2.5$, 2.4, and 3.2, respectively.

Staus with $\beta\gamma > 0.9$ as muons in the simulation of triggering.['06 Ellis,Raklev,Oye]

Event Selection

Two stau candidates for neutralino reconstruction
(consistent with measured stau mass)

$$\beta' - 0.05 < \beta_{\rm meas} < \beta' + 0.05 \ ,$$
$$\beta' = \sqrt{p_{\rm meas}^2/(p_{\rm meas}^2 + m_{\tilde{\tau}_1}^2)}$$

Both have pT>20GeV, βγ>0.4

One of the stau candidates must have βγ<2.2

$M_{\rm eff}$ >800GeV ⟶ SM background negligible

['00 Ambrosanio,Mele,Petrarca,Polesello,Rimoldi]

One tau-jet candidate

pT>40GeV

tau-tag efficiency 50%
mis-tag probability 1%

Part III

Natural Gravitino Dark Matter

Natural Gravitino Dark Matter

Thermally produced gravitino

$$\Omega_{3/2}h^2 \simeq 0.2 \times \left(\frac{T_R}{10^8\,\mathrm{GeV}}\right)\left(\frac{1\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\mathrm{gluino}}}{1\mathrm{TeV}}\right)^2$$

We need to choose reheating temperature to obtain the observed DM density.

In our model, the scalar component of the SUSY breaking multiplet provides the gravitino.

↓

Gravitino Dark Matter density is determined by low-energy parameters

Natural Gravitino Dark Matter

Scenario

$$V(s) \simeq m_S^2 |s|^2 - 2m^2 |w_0| s$$

$$m_S^4 = 4\frac{m^4}{\Lambda^2}$$

$$|w_0| \simeq m^2 M_{\rm Pl}/\sqrt{3},$$

$$m_S \simeq 400\,\mathrm{GeV} \left(\frac{\mathrm{m_{bino}}}{200\,\mathrm{GeV}}\right)^{1/2} \left(\frac{\mathrm{m_{3/2}}}{500\,\mathrm{MeV}}\right)^{1/2}$$

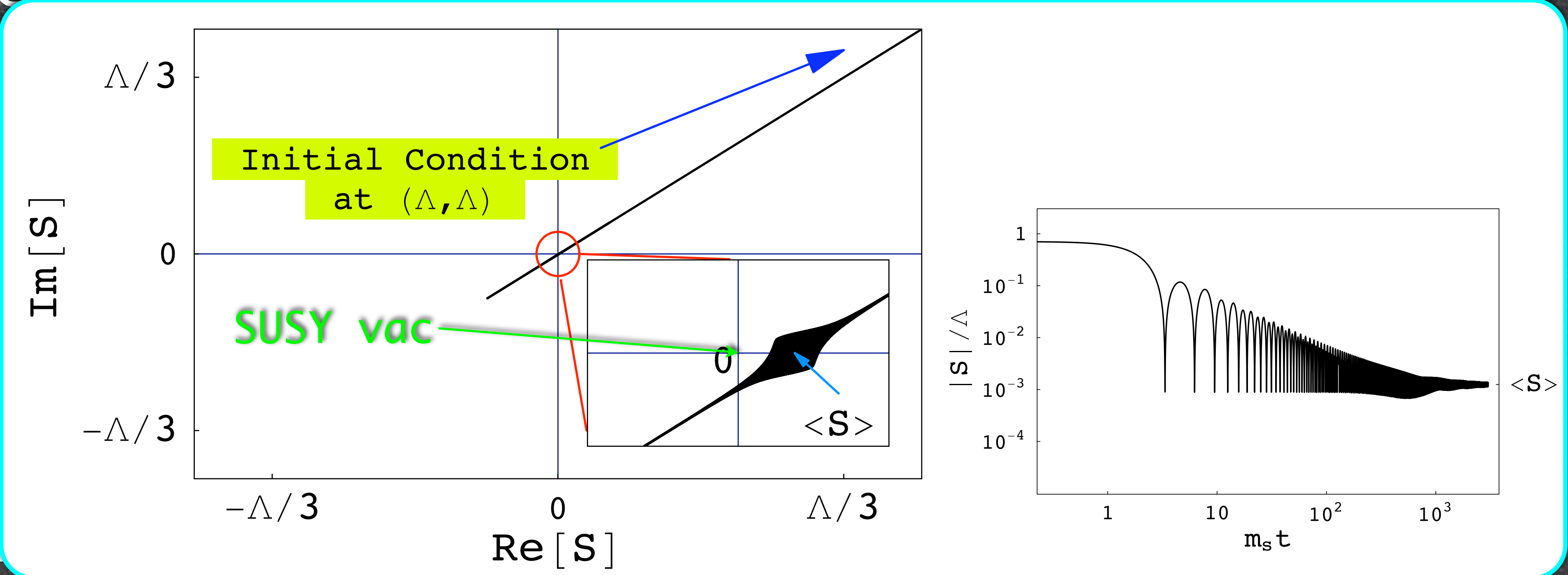
1. During Inflation $|s| \to O(\Lambda \simeq M_{\rm GUT})$
2. $H < m_S$ s starts oscillating about its vev

   s dominates the energy density of the universe
3. s decays into MSSM particles and gravitinos

   DM density is only determined by branching ratios

Natural Gravitino Dark Matter

Scenario



1.

2. $H < m_S$ s starts oscillating about its vev

s dominates the energy density of the universe

3. s decays into MSSM particles and gravitinos

DM density is only determined by branching ratios

Natural Gravitino Dark Matter

Branching ratio

Higgs modes (main mode for $m_S > 2 \times m_h$)

$$\mathcal{L}_{\tilde{f}} = \frac{m_{\tilde{f}}^2}{\langle S \rangle} S \tilde{f}^\dagger \tilde{f} + \text{h.c.} \quad (\tilde{f} \to h)$$

GMSB effects

$$\Gamma_H = \frac{x_H^2 N^2}{1536\pi} \frac{m_S^3}{M_{\rm Pl}^2} \left(\frac{m_S}{m_{3/2}} \right)^8$$

$$x_H = \frac{g_2^4}{(4\pi)^4} \cdot \frac{3}{4} + \frac{g_Y^4}{(4\pi)^4} \cdot \frac{5}{3} \cdot \frac{1}{4} \simeq 6 \times 10^{-6}$$

$$\tau_S = 5 \times 10^{-5} \text{ sec} \times N^{-2} \left(\frac{m_S}{400 \text{ GeV}} \right)^{-11} \left(\frac{m_{3/2}}{500 \text{ MeV}} \right)^8$$

Gravitino modes

$$\Gamma_{3/2} = \frac{1}{96\pi} \frac{m_S^3}{M_{\rm Pl}^2} \left(\frac{m_S}{m_{3/2}} \right)^2$$

Natural Gravitino Dark Matter

Branching ratio

Higgs modes (main mode for $m_S > 2 \times m_h$)

$$\mathcal{L}_{\tilde{f}} = \frac{m_{\tilde{f}}^2}{\langle S \rangle} S \tilde{f}^\dagger \tilde{f} + \text{h.c.} \quad (\tilde{f} \to h)$$

GMSB effects

$$\Gamma_H = \frac{x_H^2 N^2}{1536\pi} \frac{m_S^3}{M_{\text{Pl}}^2} \left(\frac{m_S}{m_{3/2}} \right)^8 \qquad x_H = \frac{g_2^4}{(4\pi)^4} \cdot \frac{3}{4} + \frac{g_Y^4}{(4\pi)^4} \cdot \frac{5}{3} \cdot \frac{1}{4}$$

$$\simeq 6 \times 10^{-6}$$

$$\tau_S = 5 \times 10^{-5} \text{ sec} \times N^{-2} \left(\frac{m_S}{400 \text{ GeV}} \right)^{-11} \left(\frac{m_{3/2}}{500 \text{ MeV}} \right)^8$$

Gravitino modes

$$B_{3/2} = 2 \times 10^{-6} \times \left(\frac{m_S}{400\text{GeV}} \right)^{-6} \left(\frac{m_{3/2}}{500\text{MeV}} \right)^6$$

Natural Gravitino Dark Matter

Gravitino abundance

yield of the gravitino

$$\frac{n_{3/2}}{s} = \frac{3}{4}\frac{T_d}{m_S} B_{3/2} \times 2\ , \quad T_d \simeq 0.5 \times \sqrt{\Gamma_H M_{\rm Pl}}\ , B_{3/2} = \Gamma_{3/2}/\Gamma_H$$

mass density parameter of gravitino

$$\boxed{\Omega_{3/2} h^2 = 0.09 \times \left(\frac{m_S}{400\ \mathrm{GeV}}\right)^{-3/2} \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^3}$$

$$\Omega_{\rm CDM} h^2 = 0.10 \pm 0.02$$

Natural Gravitino Dark Matter

Gravitino abundance

yield of the gravitino

$$\frac{n_{3/2}}{s} = \frac{3}{4}\frac{T_d}{m_S} B_{3/2} \times 2\ , \quad T_d \simeq 0.5 \times \sqrt{\Gamma_H M_{\rm Pl}}\ , B_{3/2} = \Gamma_{3/2}/\Gamma_H$$

mass density parameter of gravitino

$$\boxed{\Omega_{3/2} h^2 = 0.1 \times \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^{3/2} \left(\frac{\Lambda}{1 \times 10^{16}\ \mathrm{GeV}}\right)^{3/2}}$$

$$\Omega_{\rm CDM} h^2 = 0.10 \pm 0.02$$

Natural Gravitino Dark Matter

Sweet Spot (again)

gravitino Dark Matter

$$\Omega_{3/2}h^2 = 0.1 \times \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^{3/2} \left(\frac{\Lambda}{1 \times 10^{16}\ \mathrm{GeV}}\right)^{3/2}$$

Gauge Mediated masses

$$m_{\mathrm{gaugino}} \simeq m_{\mathrm{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

Giudice-Masiero mechanism + PQ-symmetry

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)$$

Natural Gravitino Dark Matter

Sweet Spot (again)

gravitino Dark Matter

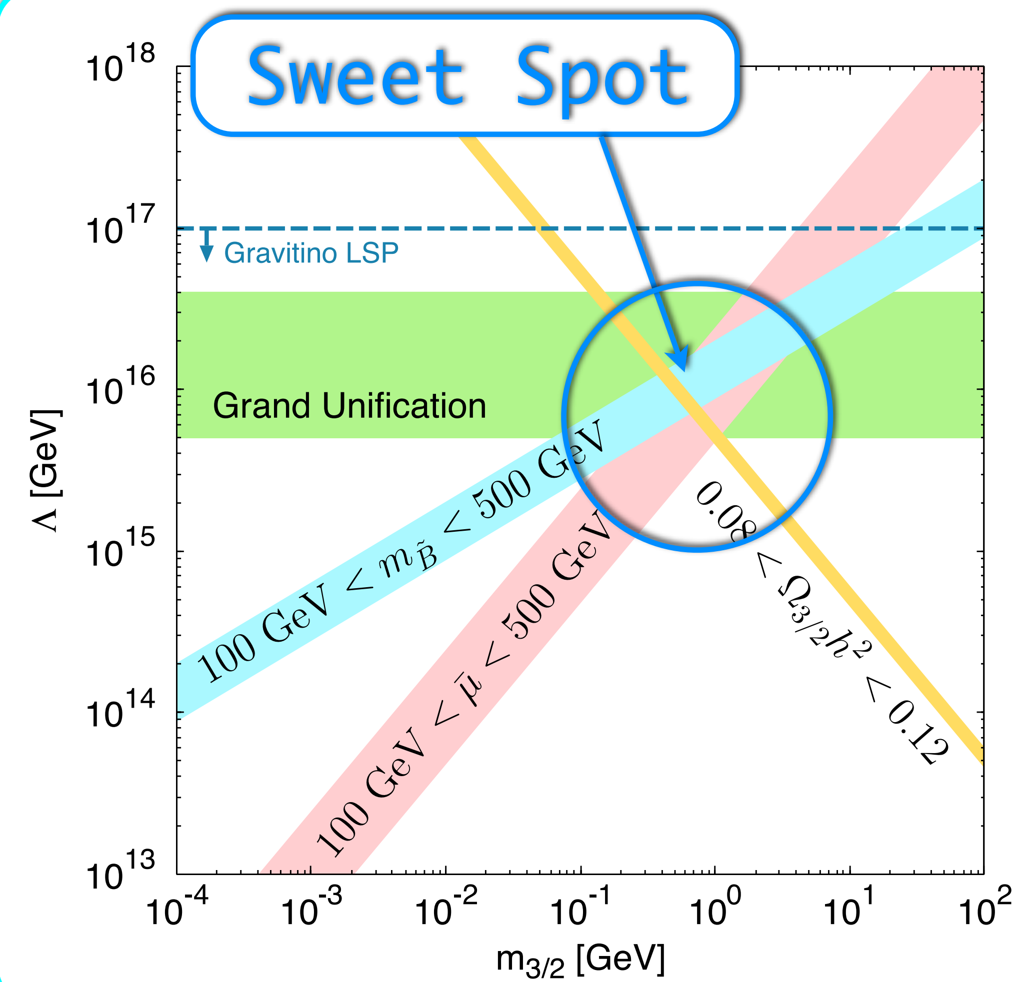
$$\Omega_{3/2}h^2 = 0.1 \times \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^{3/2}$$

Gauge Mediated masses

$$m_{\mathrm{gaugino}} \simeq m_{\mathrm{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_3$$

Giudice-Masiero mechanis

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)$$



Natural Gravitino Dark Matter

The abundance of the stau from the S-decay $T_d \ll T_f$

For $n_{\tilde{\tau}}^{\text{from } S} \langle \sigma v \rangle \gg H$

$\longrightarrow$ staus still annihilate

$$\boxed{\frac{n_{\tilde{\tau}}^{\text{final}}}{s} \simeq \left.\frac{H}{\langle \sigma v \rangle s}\right|_{T_d} \simeq \frac{C}{\langle \sigma v \rangle M_{\text{PL}} T_d}}$$

instantaneous annihilation
stops at mean free path > Hubble length

cf. $$\frac{n_{\tilde{\tau}}^{\text{thermal}}}{s} \simeq \left.\frac{H}{\langle \sigma v \rangle s}\right|_{T_f} \simeq \frac{C}{\langle \sigma v \rangle M_{\text{PL}} T_f}$$

$$T_f \simeq m_{\text{NLSP}}/20$$

Natural Gravitino Dark Matter

The abundance of the stau from the S-decay $T_d \ll T_f$

For $n_{\tilde{\tau}}^{\text{from } S} \langle \sigma v \rangle \gg H$

→ staus still annihilate

$$\boxed{\frac{n_{\tilde{\tau}}^{\text{final}}}{s} \simeq \left.\frac{H}{\langle \sigma v \rangle s}\right|_{T_d} \simeq \frac{C}{\langle \sigma v \rangle M_{\text{PL}} T_d}}$$

instantaneous annihilation

stops at mean free path > Hubble length

$$\boxed{\frac{n_{\tilde{\tau}}^{\text{final}}}{s} \simeq \left(\frac{T_f}{T_d}\right) Y_{\tilde{\tau}}^{\text{thermal}}}$$

enhanced!

Natural Gravitino Dark Matter

The abundance of the stau from the S-decay $T_d \ll T_f$

For $n_{\tilde{\tau}}^{\mathrm{from}\,S} \langle \sigma v \rangle \gg H$

→ staus still annihilate

$$\frac{n_{\tilde{\tau}}^{\mathrm{final}}}{s} \simeq \left. \frac{H}{\langle \sigma v \rangle s} \right|_{T_d} \simeq \frac{C}{\langle \sigma v \rangle M_{\mathrm{PL}} T_d}$$

instantaneous annihilation

stops at mean free path > Hubble length

by using

$$Y_{\tilde{\tau}}^{\mathrm{thermal}} \simeq 10^{-13} \left(\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}} \right)$$

Natural Gravitino Dark Matter

The abundance of the stau from the S-decay $T_d \ll T_f$

For $n_{\tilde{\tau}}^{\mathrm{from}\,S}\langle\sigma v\rangle \gg H$

→ staus still annihilate

$$\boxed{\frac{n_{\tilde{\tau}}^{\mathrm{final}}}{s} \simeq \left.\frac{H}{\langle\sigma v\rangle s}\right|_{T_d} \simeq \frac{C}{\langle\sigma v\rangle M_{\mathrm{PL}} T_d}}$$

instantaneous annihilation
stops at mean free path > Hubble length

$$\boxed{Y_{\tilde{\tau}}^{\mathrm{final}} \simeq 10^{-11.3}\left(\frac{T_f}{5\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{MeV}}{T_d}\right)\left(\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}\right)}$$

Natural Gravitino Dark Matter

The abundance of the stau from the S-decay $T_d \ll T_f$

For $n_{\tilde{\tau}}^{\text{from } S}\langle\sigma v\rangle \gg H$

→ staus still annihilate

$$\boxed{\frac{n_{\tilde{\tau}}^{\text{final}}}{s} \simeq \left.\frac{H}{\langle\sigma v\rangle s}\right|_{T_d} \simeq \frac{C}{\langle\sigma v\rangle M_{\text{PL}} T_d}}$$

instantaneous annihilation

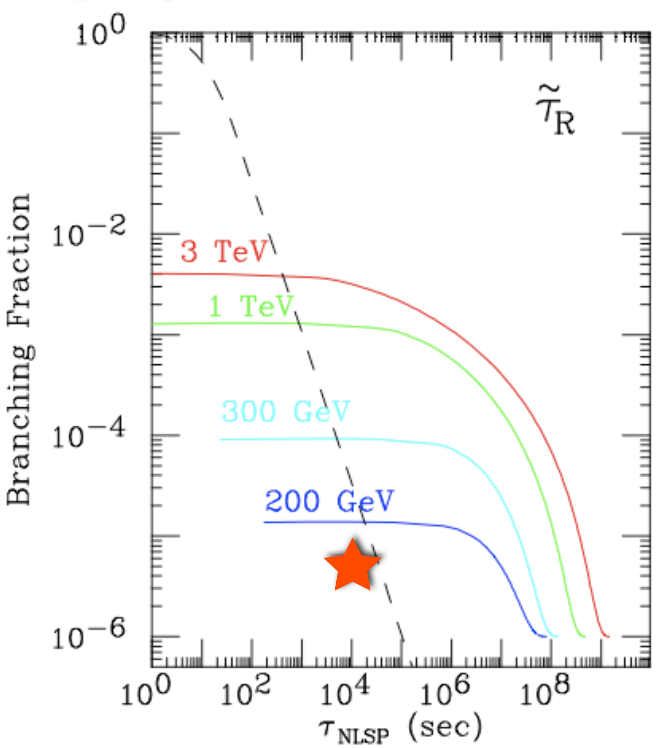
stops at mean free path > Hubble length

$$\boxed{\Omega_{\tilde{\tau}}^{\text{final}} h^2 \simeq 0.1 \left(\frac{T_f}{5\,\text{GeV}}\right)\left(\frac{100\,\text{MeV}}{T_d}\right)\left(\frac{m_{\tilde{\tau}}}{100\,\text{GeV}}\right)}$$

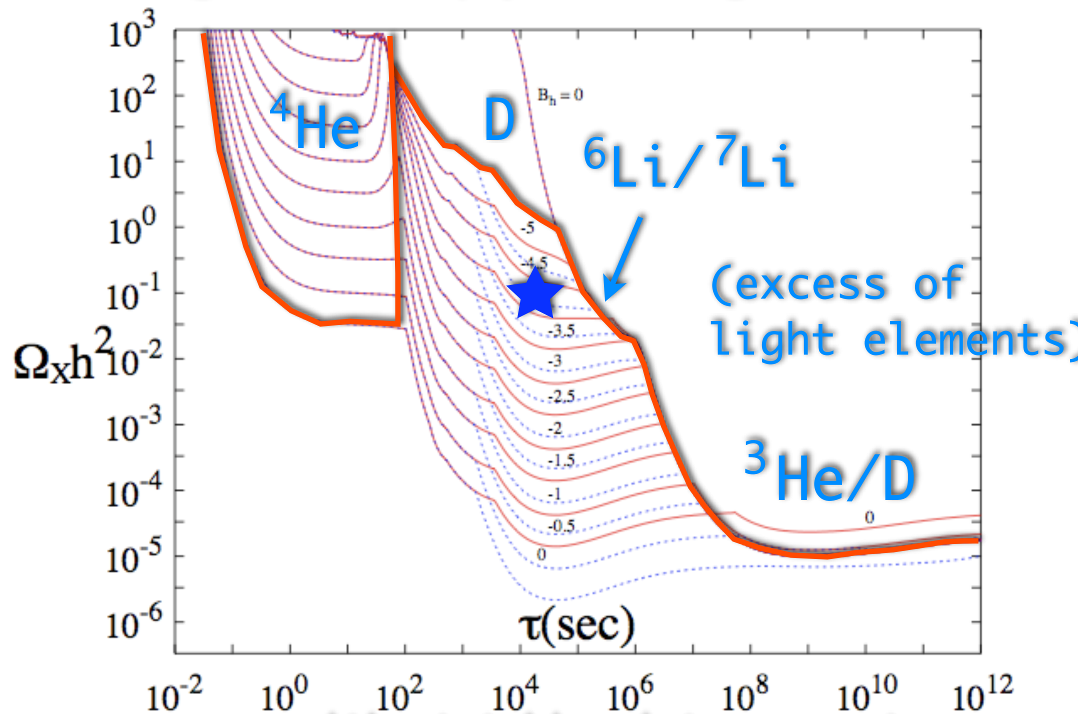
Natural Gravitino Dark Matter

BBN constrains from the stau decay

[Feng et.al. hep-ph/0404198]



[Jedamzik hep-ph/0604251]



without taking into account
stau catalysed processes

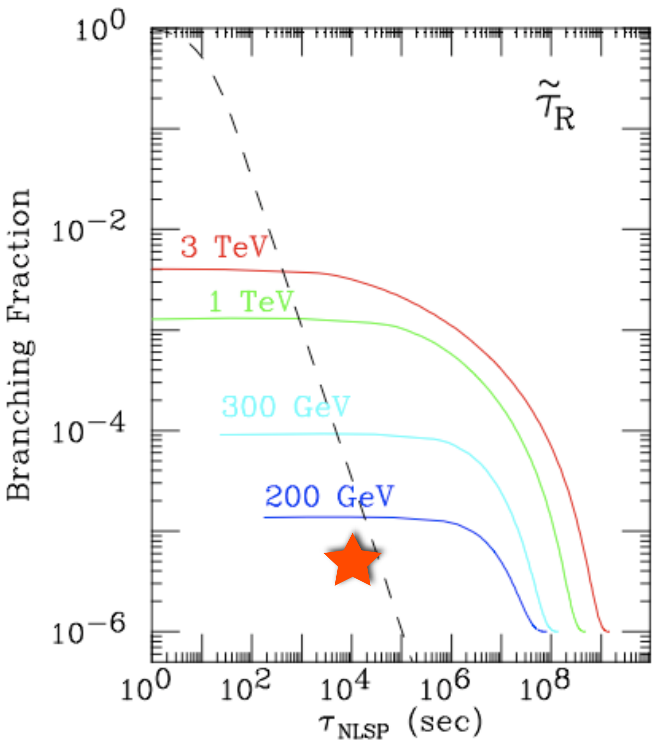
lifetime:

$$(\tilde{\tau} \longrightarrow \tau \tilde{G}) \quad \tau_{\tilde{\tau}} \simeq 6 \times 10^4 \sec \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{\tau}}}\right)^5 \left(\frac{m_{3/2}}{1\,\mathrm{GeV}}\right)^2$$

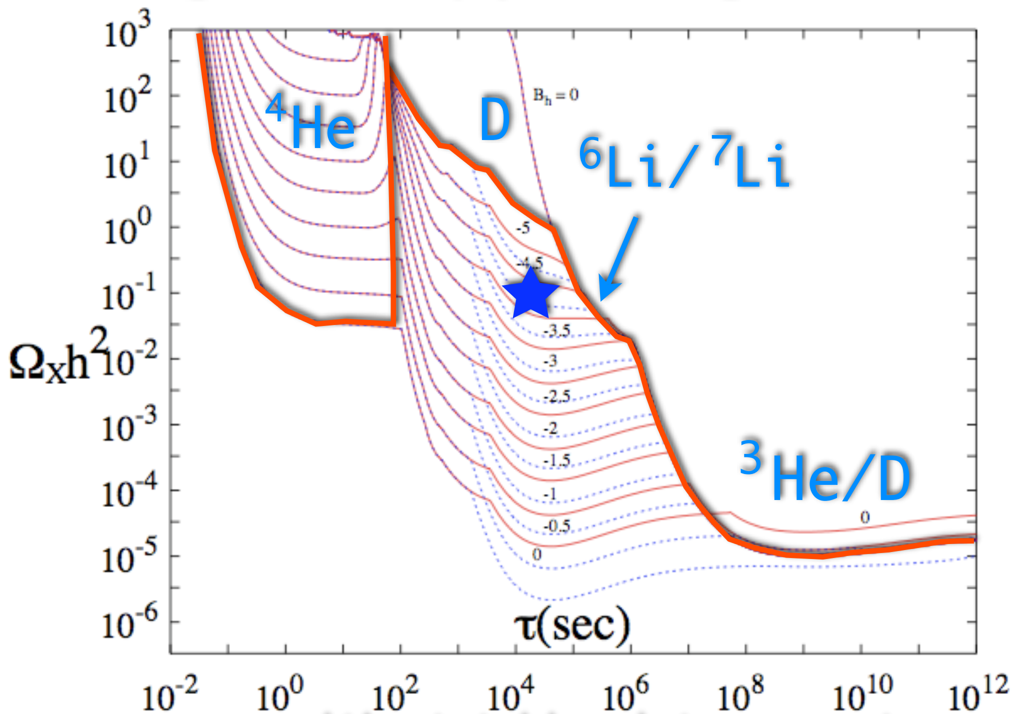
Natural Gravitino Dark Matter

BBN constrains from the stau decay

[Feng et.al. hep-ph/0404198]



[Jedamzik hep-ph/0604251]



without taking into account
stau catalysed processes

$$B_{\rm had} \equiv \frac{\Gamma(\tilde{l} \to l Z \tilde{G}) B_{\rm h}^Z + \Gamma(\tilde{l} \to l' W \tilde{G}) B_{\rm h}^W + \Gamma(\tilde{l} \to l' q \bar{q} \tilde{G})}{\Gamma(\tilde{l} \to l \tilde{G})}$$

$$B_{\rm h}^Z, B_{\rm h}^W \simeq 0.7$$

Simple Gauge Mediation

Messenger particle (5,5*)

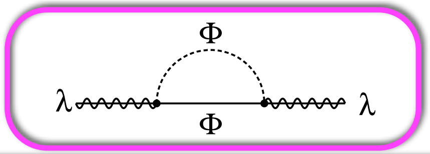
$$W = kX\Phi\bar{\Phi},$$

Spurion (SUSY-, ~~SUSY~~-mass)

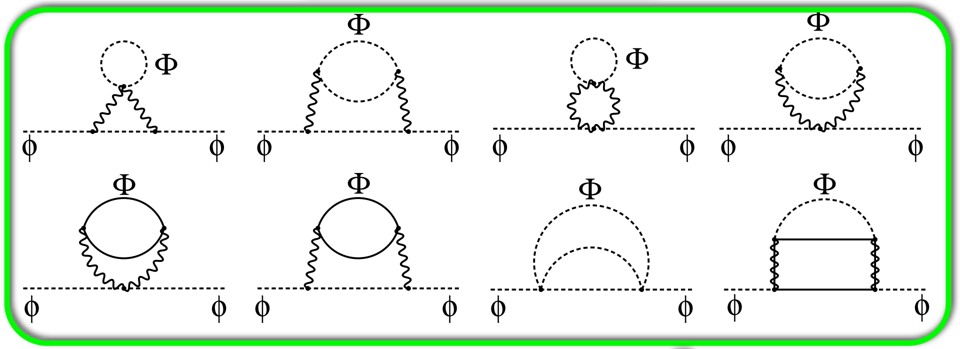
$$\langle X \rangle = M + \theta^2 F,$$

mass splitting of messenger bosons

$$\begin{pmatrix} k^2|M|^2 & kF \\ kF^* & k^2|M|^2 \end{pmatrix} \longrightarrow |kM|^2 \pm |kF|$$



Gaugino



scalar mass^2

At the messenger scale $(M_{\text{mess}} = kM, M \gg \sqrt{F/k})$

$$m_{\text{gaugino}} \simeq \frac{\alpha}{4\pi}\frac{F}{M}$$

$$m^2_{\text{scalar}} \simeq 2C_2\left(\frac{\alpha}{4\pi}\right)^2\left|\frac{F}{M}\right|^2$$

Simple Gauge Mediation

Effective operator Method ['97 Giudice & Rattazzi]

After integrating out the messengers

$$\mathcal{L} \ni f(X) W^\alpha W_\alpha, \qquad Z(X, X^\dagger) Q^\dagger Q$$

$$m_{\text{gaugino}} = \frac{1}{2} \frac{\partial \ln f(X)}{\partial \ln X} \frac{\langle F \rangle}{\langle X \rangle}$$

$$m^2_{\text{scalar}} = -\frac{\partial \ln Z(X, X^\dagger)}{\partial \ln X \partial \ln X^\dagger} \left| \frac{\langle F \rangle}{\langle X \rangle} \right|^2$$

The solution of f and Z at the 1-loop level

$$f(X) = \frac{1}{\alpha(M_*)} + \frac{b_H}{2\pi} \ln \frac{X}{M_*} + b_L \ln \frac{\mu_R}{X}$$

$$Z(X, X^\dagger) = \left(\frac{\alpha(M_*)}{\alpha(\sqrt{X X^\dagger})} \right)^{\frac{C_2}{b_H}} \left(\frac{\alpha(\sqrt{X X^\dagger})}{\alpha(\mu_R)} \right)^{\frac{C_2}{b_L}}$$

Simple Gauge Mediation

Effective operator Method ['97 Giudice & Rattazzi]

After integrating out the messengers

$$\mathcal{L} \ni f(X) W^\alpha W_\alpha, \qquad Z(X, X^\dagger) Q^\dagger Q$$

Around the Messenger scale,
relevant effective terms are;

$$f(X) \sim \frac{1}{2g^2} - \frac{1}{(4\pi)^2} \ln X \quad \tilde{Z}(X, X) \sim 1 - \frac{g^4}{(4\pi)^4} C_2 (\ln X X^\dagger)^2$$

Again, the soft terms are;

$$m_{\text{gaugino}} \simeq \frac{\alpha}{4\pi} \frac{F}{M} \qquad m^2_{\text{scalar}} \simeq 2C_2 \left(\frac{\alpha}{4\pi}\right)^2 \left|\frac{F}{M}\right|^2$$

Neutrino Mass

We can assign the PQ-charge up to B-L symmetry

$$PQ(Q) = PQ(\bar{U}) = PQ(\bar{D}) = PQ(L) = PQ(\bar{E}) = -1/2$$

or

$$PQ(Q) = -1/3 \quad PQ(\bar{U}) = PQ(\bar{D}) = -2/3$$

$$PQ(L) = -1 \qquad PQ(\bar{E}) = 0$$

By using the later assignment, the Majorana neutrino mass can be write down

$$W = \frac{LH_u LH_u}{M_N}$$

see saw ['79 T.Yanagida]

Electric Dipole Moment

$$\theta_{\rm CP} = {\rm Arg}(\mu(B\mu)^* m_{1/2}, m_{1/2} A^*) = O(m_{3/2}/m_{1/2}) = O(10^{-2})$$

$$\mathcal{L}_{\rm EDM} = \frac{i}{2} d_e \bar{e} \sigma^{\alpha\beta} \gamma_5 e F_{\alpha\beta}$$

$$d_e^{\rm SUSY} \sim \sin\theta_{\rm CP} \frac{g_2^2 M_2 m_e \mu \tan\beta}{32\pi^2 m_{\tilde{e}}^4}$$

$$|d_e| < 0.7 \times 10^{-26} cm \simeq 0.4 \times 10^{-12} {\rm GeV}^{-1}$$

['96 Gabbiani et.al.]

The constraint is satisfied for

$$\boxed{\begin{array}{l} m_{\rm susy} > 300\,{\rm GeV} \\ m_{3/2} < 1\,{\rm GeV} \end{array}}$$

Upper bound on the Messenger Mass

The introduction of the messenger interactions results in the radiative corrections to S direction.

$$W = kSf\bar{f}$$

$$V(S) = m^4 \left(\frac{4}{\Lambda^2}|S|^2 + \frac{k^2 N}{(4\pi)^2} \log\left(\frac{k^2|S|^2}{\Lambda^2} \right) \right) - (2m_{3/2}m^2 S + \mathrm{h.c.}) \ .$$

In order the radiative correction not to destabilize the SUSY breaking vacuum, we need to require,

$$k < 3 \times 10^{-3} \left(\frac{N}{25} \right)^{-1/2} \left(\frac{\Lambda}{1 \times 10^{16}\ \mathrm{GeV}} \right) \ .$$

$$M_{\mathrm{mess}} < 4 \times 10^{10}\ \mathrm{GeV} \left(\frac{N}{25} \right)^{-1/2} \left(\frac{\Lambda}{1 \times 10^{16}\ \mathrm{GeV}} \right)^3$$

Entropy Production from S-decay

The pre-existent quantities such as gravitino abundance or the baryon asymmetry is diluted by a factor

$$\Delta^{-1} \simeq \frac{T_d}{T_{\rm dom}} \simeq \begin{cases} \dfrac{T_d}{T_R}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R < T_{\rm osc}), \\ \dfrac{T_d}{T_{\rm osc}}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R > T_{\rm osc}). \end{cases}$$

$|S_0|$:Initial amplitude

$$T_{\rm osc} \simeq 0.3 \times \sqrt{M_{\rm Pl} m_S} \simeq 8 \times 10^9\,{\rm GeV} \times \left(\frac{m_S}{400\,{\rm GeV}}\right)^{1/2}$$

the temperature when S starts oscillating

$$T_{\rm dom} = \min[T_R, T_{\rm osc}] \times \left(\frac{|S_0|}{\sqrt{3}M_{\rm PL}}\right)^2$$

the temperature when S osci. dominates the universe

Entropy Production from S-decay

The pre-existent quantities such as gravitino abundance or the baryon asymmetry is diluted by a factor

$$\Delta^{-1} \simeq \frac{T_d}{T_{\rm dom}} \simeq \begin{cases} \dfrac{T_d}{T_R}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R < T_{\rm osc}), \\ \dfrac{T_d}{T_{\rm osc}}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R > T_{\rm osc}). \end{cases}$$

$T_R < T_{\rm osc}$ $\quad |S_0| = O(M_{\rm GUT})$

$$\Delta^{-1} \simeq 10^{-4}\left(\frac{T_R}{10^8\,{\rm GeV}}\right)^{-1}$$

Entropy Production from S-decay

The dilution factor of the NLSP is given by

$$\Delta^{-1} \simeq \mathrm{Max}[(T_d/T_f)^3, T_d/(T_{\mathrm{dom}}T_f)^{1/2}]$$

$$T_f \simeq m_{\mathrm{NLSP}}/20$$

$T_R < 10^{10}\mathrm{GeV}$ $|S_0| = O(M_{\mathrm{GUT}})$

$$\Delta^{-1} \simeq 0.3 \times 10^{-3} \left(\frac{10^8}{T_R}\right)^{1/2}$$

UV completion and Grand Unification

An example of UV-model

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$
$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$\uparrow$ (One-loop calculation)

$$W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} XY \ ,$$ O'Raifeartaigh Model

$$W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q X + M_q q \bar{q} \ ,$$ (PQ-sym)

Can we make a model which is consistent with GUT?

UV completion and Grand Unification

An example of a GUT consistent UV-model

’06 Kitano SU(5)XSO(6) Product group GUT model

	$SU(5)_{GUT}$	$SO(6)_H$	$U(1)_{PQ}$
S	$\mathbf{1}$	$\mathbf{1}$	2
M	$\mathbf{1}+\mathbf{24}$	$\mathbf{1}$	0
X	$\mathbf{1}$	$\mathbf{6}$	-1
$q,\,\bar{q}$	$\mathbf{5},\,\bar{\mathbf{5}}$	$\mathbf{6}$	0
$H,\,\bar{H}$	$\mathbf{5},\,\bar{\mathbf{5}}$	$\mathbf{1}$	1

$$
\begin{aligned}
W = m^2 S + m_{\rm GUT}^2 Tr[M] - m_{\rm GUT} Tr[MM] + \cdots \\
+ S X^i X^i + \bar{q}^i M q^i + \bar{q}^i H X^i + q^i \bar{H} X^i
\end{aligned}
$$

UV completion and Grand Unification

An example of a GUT consistent UV-model

$$\langle M \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v & \\ & & & & v \end{pmatrix} \quad \langle q \rangle = \begin{pmatrix} v & & & iv & & \\ & v & & & iv & \\ & & v & & & iv \\ & & & & & \\ & & & & & \end{pmatrix} \quad \langle \bar{q} \rangle = \begin{pmatrix} v & & & -iv & & \\ & v & & & -iv & \\ & & v & & & -iv \\ & & & & & \\ & & & & & \end{pmatrix}$$

SU(5) SO(6) SO(6)

$$v = O(M_{\mathrm{GUT}})$$

GUT: SU(5)XSO(6)

MSSM: SU(3)XSU(2)XU(1)

UV completion and Grand Unification

Doublet-Triplet Splitting

$$X^i \langle q^i \rangle \bar{H} = (X^1 X^2 X^3 X^4 X^5 X^6) \begin{pmatrix} v & & & iv & & \\ & v & & & iv & \\ & & v & & & iv \\ & & & & & \\ & & & & & \\ & & & & & \end{pmatrix} \begin{pmatrix} \bar{H}_c^1 \\ \bar{H}_c^2 \\ \bar{H}_c^3 \\ H_d^1 \\ H_d^2 \end{pmatrix}$$

$$= M_{XY} X_c \bar{Y} \qquad X_c = X^i + iX^{i+3} (i = 1, 2, 3)$$

$$\bar{Y} = \bar{H}_c$$

$\downarrow$ O'Raifeartaigh Model

$$W = m^2 S + S X_c \bar{X}_c + M_{XY}(X_c \bar{Y} + \bar{X}_c Y)$$

$$+ (X_c \bar{q}_c + \bar{X}_c q_c)\bar{H} + (X_c \bar{q}_{\bar{c}} + \bar{X}_c q_{\bar{c}})H + M_q(q_c \bar{q}_{\bar{c}} + \bar{q}_c q_{\bar{c}})$$

UV completion and Grand Unification

$$W = m^2 S + S X_c \bar{X}_c + M_{XY}(X_c \bar{Y} + \bar{X}_c Y)$$
$$+(X_c \bar{q}_c + \bar{X}_c q_c)\bar{H} + (X_c \bar{q}_{\bar{c}} + \bar{X}_c q_{\bar{c}})H + M_q(q_c \bar{q}_{\bar{c}} + \bar{q}_c q_{\bar{c}})$$

$$\Big\downarrow \quad \text{One-loop effects}$$

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$
$$+ \left(\frac{c_\mu S H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$